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## Implications of the Optical Observations of Isolated Neutron Stars

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### **Abstract.**

Observations of the 5 confirmed optical pulsars indicate that the peak emission scales according to the outer field strength. We show that this gives further confirmation that a simple phenomenological models such as Pacini and Salvati (1987) still have validity. Furthermore we show that the Crab pulsar exhibits unpulsed emission which further complicate any studies of the thermal emission from Isolated Neutron Stars.

### 1. Introduction

Since the first optical observations of the Crab pulsar in the late 1960s (Cooke et al 1969) only 4 more pulsars have been seen to pulsate optically (Middleditch and Pennypacker (1985); Wallace et al (1977); Shearer et al (1997); Shearer et al (1998)). Four of these five pulsars are probably too distant to have any detectable thermal emission. For the fifth (and faintest) pulsar, PSR 0633+17, emission has been shown to be non-thermal (Martin et al 1998). Many suggestions have been made concerning the optical emission process for these young and middle-aged pulsars. However the most successful phenomenological model (both in terms of its simplicity and longevity) has the proposed by Pacini (1972) and in modified form by Pacini and Salvati (1983, 1987). In general they proposed that the high energy emission comes from electrons radiating via synchrotron processes in the outer regions of the magnetosphere.

In recent years a number of groups of carried out detailed simulations of the high-energy processes. These models divide into two groups - between emission low in the magnetosphere (polar cap models) and those with the acceleration nearer to the light cylinder (outer-gap models). Both models have problems explaining the observed features of the limited selection of high energy emitters. Both models suffer from arbitrary assumptions in terms of the sustainability of the outer-gap and the orientation of the pulsar's magnetic field to both the observers line of sight and the rotation axis. Furthermore observational evidence, see for example Eikenberry & Fazio (1997), severely limits the applicability of the outer-gap to the emission from the Crab. However they have their successes - the total polar-cap emission can be understood in terms of the Goldreich and Julian

current from in or around the cap; the Crab polarisation sweep is accurately produced by an outer-gap variant Romani et al (1995).

It is the failure of the detailed models to explain the high energy emission which has prompted this work. We have taken a phenomenological approach to test whether Pacini type scaling is still applicable. Our approach has been to try and restrict the effects of geometry by taking the peak luminosity as a scaling parameter rather than the total luminosity. In this regard we are removing the duty cycle term from PS87. Furthermore it is our opinion that to first order the peak emission represents the local power density along the observer's line of site.

## 2. The Phenomenology of Magnetospheric Emission

The three brightest pulsars (Crab, Vela and PSR 0540-69) are also amongst the youngest. Table 1 shows the basic parameters for these objects. However all the pulsars have very different pulse shapes resulting in a very different ratio between the integrated flux and the peak flux. Table 1 also shows this peak emission (taken as the emission at the top of the largest peak). Their distances imply that the thermal emission should be low (in all cases < 1% of the observed emission).

Of all the optical pulsars PSR 0633+17 is perhaps the most controversial. Early observations (Halpern & Tytler (1988), and Bignani et al (1988)) indicated that Geminga was an  $\approx 25.5$  mv object. Subsequent observations including HST photometry appeared to support a thermal origin for the optical photons, albeit requiring an arbitrary assumption of cyclotron resonance feature in the optical (Mignani et al, 1998). The optical observations of Shearer et al (1998) combined with spectroscopic observations (Martin et al, 1998) contradict this view. Figures 1 and 2 show how this misunderstanding could have arisen. Figure 1, based upon data from Bignani et al (1998) shows the integrated photometry. It would be possible to fit a black body curve through this, but only with the *a posteriori* fitting of a cyclotron resonance feature at about 5500 Å. Figure 2 however shows the same point plotted on top of the Martin et al spectra, we have also included the pulsed B point. This combined data set indicates a flat spectrum consistent with magnetospheric emission, without the requirement for such an *ad hoc* feature. It was on the basis of these results that Golden & Shearer (1999) were able to give an upper limit of  $R_\infty$  of about 10km.

With PSR 0656+14 there is a discrepancy between the radio distance based upon the dispersion measure and the best fits to the X-Ray data. From radio dispersion measure a distance of  $760 \pm 190$  pc can be derived at odds with the X-ray distance of  $250 - 280$  pc from  $N_H$  galactic models. Clearly more observations are needed to determine a parallax.

Figure 2 shows the relationship between the peak luminosity with the outer magnetic field. A regression of the form  $PeakLuminosity = a * B^b$  was determined for the peak luminosity this lead to a relationship of the form Peak Luminosity  $\propto B^{2.86 \pm 0.12}$  significant at the 99.5% level. From PS87 we would expect a relationship of the form Peak Luminosity  $\propto B^{\approx 4}$  for acceptable values of the energy spectrum exponent of the emitting electrons - in reasonable agreement with our derived relationship. Whilst informative it still goes no further

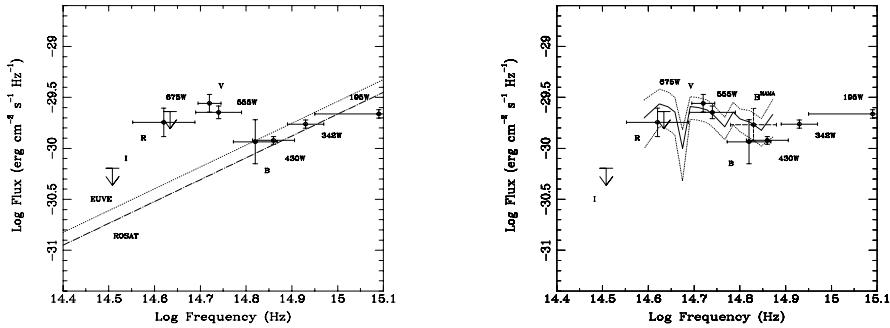


Figure 1. Spectra and Photometry of Geminga. The first plot shows the integrated photometry and the thermal fit to the ROSAT X-Ray data. The second illustrates the actual spectrum and the agreement between it and the integrated photometry. B is the pulsed flux from Shearer et al (1998).

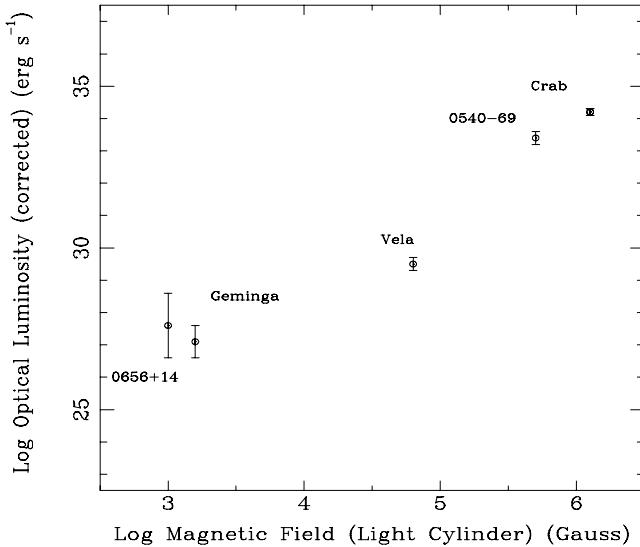


Figure 2. Outer field strength versus peak luminosity

than previous attempts to understand the phenomena of optical emission. The flattening of the peak luminosity relationship for the older, slower pulsars is consistent with their having a steeper energy spectrum than the younger pulsars. However we can state that from both polarisation studies (Smith(1988);Romani & Yadigaroglu (1995)) and from this work we expect that optical emission zone should be sited towards the outer magnetosphere. Timing studies of the size of the Crab pulse plateau indicates a restricted emission volume ( $\approx 45$  kms in lateral extent) (Golden et al (2000)). This third point, if consistent with the first two, probably points to emission coming from a geometrically defined cusp along our line of sight. Finally, there is no evidence of optical thermal emission from these 5 pulsing optical neutron stars (Martin et al (1998); this work).

### 3. Conclusion

Over the next few years (with the advent of larger telescopes and more sensitive detectors, see for example Perryman (1999) & Romani (1999)) we can confidently expect the number of optical detections of isolated neutron stars to increase. In this region of the spectrum any potential thermal component can be separated from the strongly pulsed magnetospheric emission, allowing for reliable estimates of the neutron star radius to be measured with consequent implications for equation of state models. One word of caution however - our studies (see Golden et al (1999) and this conference) indicate that the optical emission (at least from the Crab pulsar) also exhibits an unpulsed component.

**Table 1.** Main Characteristics of Optical Pulsars:  $B_S$  &  $B_{LC}$  the canonical surface and transverse magnetic field at the light cylinder respectively; Opt. Lum and Peak Lum. refer to the optical luminosity at the indicated distance in the B band

Name	D (kpc)	P (ms)	$\dot{P}$ $10^{-14}$ s/s	$B_S$ log(G)	$B_{LC}$ log (G)	Opt. Lum $\mu\text{Crab}$	Peak Lumin. $\mu\text{Crab}$
Crab	2	33	40	12.6	6.1	$10^6$	$10^6$
Vela	0.5	89	11	12.5	4.8	27	21
PSR0545-69	49	50	40	12.7	5.7	$1.1 \cdot 10^6$	$1.4 \cdot 10^5$
PSR0656+14	0.76(?)	385	1.2	12.7	3.0	1.8	0.3
PSR0633+17	0.16	237	1.2	12.2	3.2	0.3	0.1

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